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Original Articles

Integrate carbon dynamics models for assessing the impact of land use intervention on carbon sequestration ecosystem service

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ABSTRACT

The land use intervention caused a noticeable impact on carbon sequestration as an ecosystem service. To comprehensively project land use change impact on carbon sequestration, the carbon dynamics models in the ecosystem and the atmosphere were integrated, and characterization factors were calculated for different scenarios. In this study, to illustrate the proposed method, the CENTURY model was used to simulate the carbon dynamics for seven land use change scenarios under two climate change scenarios. Carbon dynamics in the atmosphere was simulated by the Bern2.5CC carbon cycle model. The impact on carbon sequestration was calculated based on the difference of carbon sequestration between the land use change scenario and the corresponding baseline and the decay of CO_2 in the atmosphere. According to the simulations, we found that carbon storages and differences of the annual carbon sequestration rate were varied among land use change scenarios and between the two climate change scenarios. After land use conversion, an equilibrium status would be obtained after 100 to 200 years of growth. By integrating the carbon dynamics model with the atmosphere, the characterization factors (CF) were calculated for life cycle assessment. The values of CFs were significantly changed in different land use change scenarios, climate change scenarios and time horizons. The comparison to the previous assessment method indicated that the previous method was too conservative. The results suggested that the method in this study could provide a more reasonable assessment of the impact of land use intervention on carbon sequestration.

1. Introduction

Ecosystem service was first used by Ehrlich and Ehrlich (1981) and became flourish in the last few decades (Fisher et al., 2009). It is defined as human benefits obtained from ecosystems. In particular, the Millennium Ecosystem Assessment (MA) did a monumental work and classified ecosystem services into four categories (MA, 2005): provisioning, regulating, cultural and supporting services. Carbon sequestration is an important ecosystem service and defined as the net annual rate of atmospheric carbon absorbed by an ecosystem. Under the requirement of mitigating climate change, carbon sequestration as a regulating service brings more interest and was intensively studied. The United Nations Framework Convention on Climate Change (UNFCCC) also advocates cooperation of all countries to enhance carbon absorption by terrestrial ecosystems (1992).

The land use intervention could significantly change carbon sequestration of an ecosystem (Searchinger et al., 2008; Lawler et al., 2014; Schulp et al., 2008). However, the estimation of carbon sequestration is complex as it is affected by many different factors, such as ecosystem type, tree stand age, soil type, elevation, initial and final land use, and the duration of land use change (Adamus et al., 2000). With the development of sophisticated model and technology, researchers can simulate carbon sequestration of an ecosystem more accurately and efficiently. Naidoo et al. (2008) mapped the global carbon sequestration using the Terrestrial Ecosystem Model (TEM). They found high carbon sequestration rate in eastern U.S., northern South American, middle Africa, southeastern China and eastern Australia. By incorporating satellite-derived NDVI, climate data and the terrestrial Carnegie-Ames-Stanford Approach (CASA) ecosystem model, the analysis of carbon sequestration efficiency in the Loess Plateau indicated a shift from a carbon source in 2000 to a carbon sink in 2008 by China's Grain to Green Project (Feng et al., 2013). Petrie et al. (2015) studied carbon dynamics in arid ecosystems using statistical regression with field observations, and found a significant increase of carbon sequestration from grassland to shrubland. Moreover, many simulation tools have been developed and available to model carbon dynamics for

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different ecosystems, such as CENTURY (Parton et al., 2001), FVS (Forest Vegetation Simulator, Dixon, 2002), CBM-CFS3 (Carbon Budget Model of the Canadian Forest Sector, Kurz et al., 2009), CO2FIX (Schelhaas et al., 2004) and ForCSv2 (Forest Carbon Succession v2.0) extension for the LANDIS-II model (Dymond et al., 2002).

Although the difficulty in carbon sequestration estimation for an ecosystem, the quantification of carbon sequestration as an ecosystem service is critical for decision making (Nelson et al., 2009). Due to the importance of carbon sequestration, the impact of a product/service on carbon sequestration of an ecosystem should be analyzed in life cycle assessment (LCA). LCA is a widely used tool to assess the environmental impact of a product/service in its life cycle. However, the analysis of carbon sequestration is usually excluded in the traditional LCA (Zhang et al., 2010b). Therefore, the development of new systematic approaches for this analysis is in demand. Zhang et al. (2010b) developed an "Ecologically-based LCA" and illustrated this method by applying to drinking cup (2010a). However, this approach is an independent method more than an extension of LCA (Othoniel et al., 2016). Impact of carbon sequestration can be also assessed by the method developed for land use impact assessment on ecosystem service (Koellner et al., 2013). In this method, the characterization factor (CF) is calculated based on the difference between current land use situation and a suitable reference. However, all those approaches were developed for static systems. In fact, the analysis of carbon sequestration impact in an ecosystem is complex and dynamic. Recently, researchers also tried to consider time-dependent dynamics when conducting LCA. Levasseur et al. (2010) developed a dynamic CF by the sum of remaining emissions in the atmosphere at different years. This method has a potential to be used as a global metric approach if incorporating with carbon dynamics model. Arbault et al. (2014) implemented dynamic model GUMBO (Global Unified Meta-model of the Biosphere) to assess the impact on ecosystem services. All these efforts significantly advance the dynamic characterization of impacts on carbon sequestration. However, more time-dependent carbon dynamics in ecosystems and in the atmosphere need to be integrated into the analysis (Yan, 2018). In this study, our objectives are 1) to integrate carbon dynamic models and develop an approach to account the impact of land use change on carbon sequestration as an ecosystem service, and 2) to use case studies to illustrate the implementation of this approach.

2. Methods

In this section, we described the model to simulate carbon dynamics for land use change in the first subsection. A method to account carbon sequestration impact in life cycle assessment was proposed in the following subsection. In the case studies, seven land use change scenarios were defined to analyze the performance of the integration of carbon dynamic model.

2.1. Simulation of carbon dynamics

The CENTURY4.0 model was used to estimate the carbon sequestration of different vegetation types during land use interventions. The CENTURY model was developed by Natural Resource Ecology Laboratory of Colorado State University and initially used for cropland/grassland simulation (Parton et al., 1987). Current developed CENTURY model was also able to estimate carbon processes of forest land. In this study, we used CENTURY model because this model was extensively validated by field observations around the world (Henderson et al., 2015). The CENTURY model was initiated by a 2000-year spin-up through a serial of management sequence using CRU mean monthly climate data. A 2000-year spin-up ensured a stable state was reached, especially soil organic carbon (SOC) equilibrium. The future climate data were simulated from twenty different Global Climate Models. To estimate the impact of land use interventions on carbon sequestration as an ecosystem service, we also modeled the carbon sequestration of the land uses without any intervention as reference scenarios (baselines).

2.2. Life cycle impact of carbon sequestration

To analyze the impact of land use interventions on carbon sequestration, original land cover before the intervention was used as a baseline. If a land use intervention induces carbon sequestration change at year 0, annual carbon sequestration at year t is $C(t)$ gC/m^2 (tC: metric ton carbon equivalent) in original land cover and $C'(t)$ gC/m^2 after intervention. Therefore, annual carbon sequestration difference $\Delta C(t)$ is $C'(t) - C(t)$.

Because carbon emissions decay in the atmosphere in the interaction of ocean-atmosphere systems (Joos et al., 2013), a discount effect should be included when calculating total impact (T) on carbon sequestration that caused by land use intervention. In this study, we assumed all the carbon emissions are CO_2, and the remaining fraction is $y(t)$ in year t. Thus,

$$T = \int_1^{TH} \frac{\Delta C(t)}{y(t)} \tag{1}$$

$$y(t) = y_0 + \sum_{i=1}^{3} y_i e^{-t/\tau_i} \tag{2}$$

where TH is the chosen time horizon; $y(t)$ is the fraction of the initial CO_2 emission in year t, while y_i and τ_i are estimated parameters. TH is 20-, 100- and 500-year in this study. The CO_2 decay model (Eq. 2) is developed according to the Bern2.5CC carbon cycle model when CO_2 concentration is 378 ppm in the atmosphere (Joos et al., 2013). The parameters are fitted based on a set of climate models: $y_0 = 0.217$, $y_1 = 0.224$, $y_2 = 0.282$, $y_3 = 0.276$, $\tau_1 = 394.4$, $\tau_2 = 36.54$, $\tau_3 = 4.304$ (Joos et al., 2013).

To incorporate the total impact into LCA, the total impact of carbon sequestration is divided by a physical unit (i.e., 1 ha/1 m^2 of land use change). In LCA study, this physical unit is recognized as functional unit (*FU*). Therefore, characterization factor (*CF*) is defined as follows:

$$\mathrm{CF} = \frac{T}{FU} \tag{3}$$

2.3. Case study

2.3.1. Site Description

We assumed that the land use interventions occurred near Nineveh, IN, the USA in 2012 (39.3152 N, 86.0512 W). This site is characterized by a humid subtropical climate with hot, humid summers and mild to cool winters. The annual average temperature is 11.6 °C, and the average annual precipitation is 1,074 mm from 1901 to 2012. This site was chosen in this study because all the simulated vegetation types (i.e., mixed forest, grassland and cropland) can be found near this site. Soil data were obtained from USDA (U.S. Department of Agriculture) soil data explorer (https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx). The soil texture was clay 18%, sand 18% and silt 64% in 2012.

2.3.2. Climate data

The historical climate data from 1901 to 2012 was downloaded from the Climate Research Unit (CRU) of the University of East Anglia (Mitchell and Jones, 2005). The climate data include monthly precipitation, average daily maximum and minimum air temperature.

The future climate data were simulations of twenty different Global Climate Models (GCM) in two climate change scenarios (medium and high greenhouse gas concentration) defined by Nakicenovic et al. (2000). The twenty GCMs were BCC-CSM1-1, BCC-CSM1-1-M, BNU-ESM, CanESM2, CCSM4, CNRM-CM5, CRIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC365, HadGEM2-ES365, INMCM, IPSL-

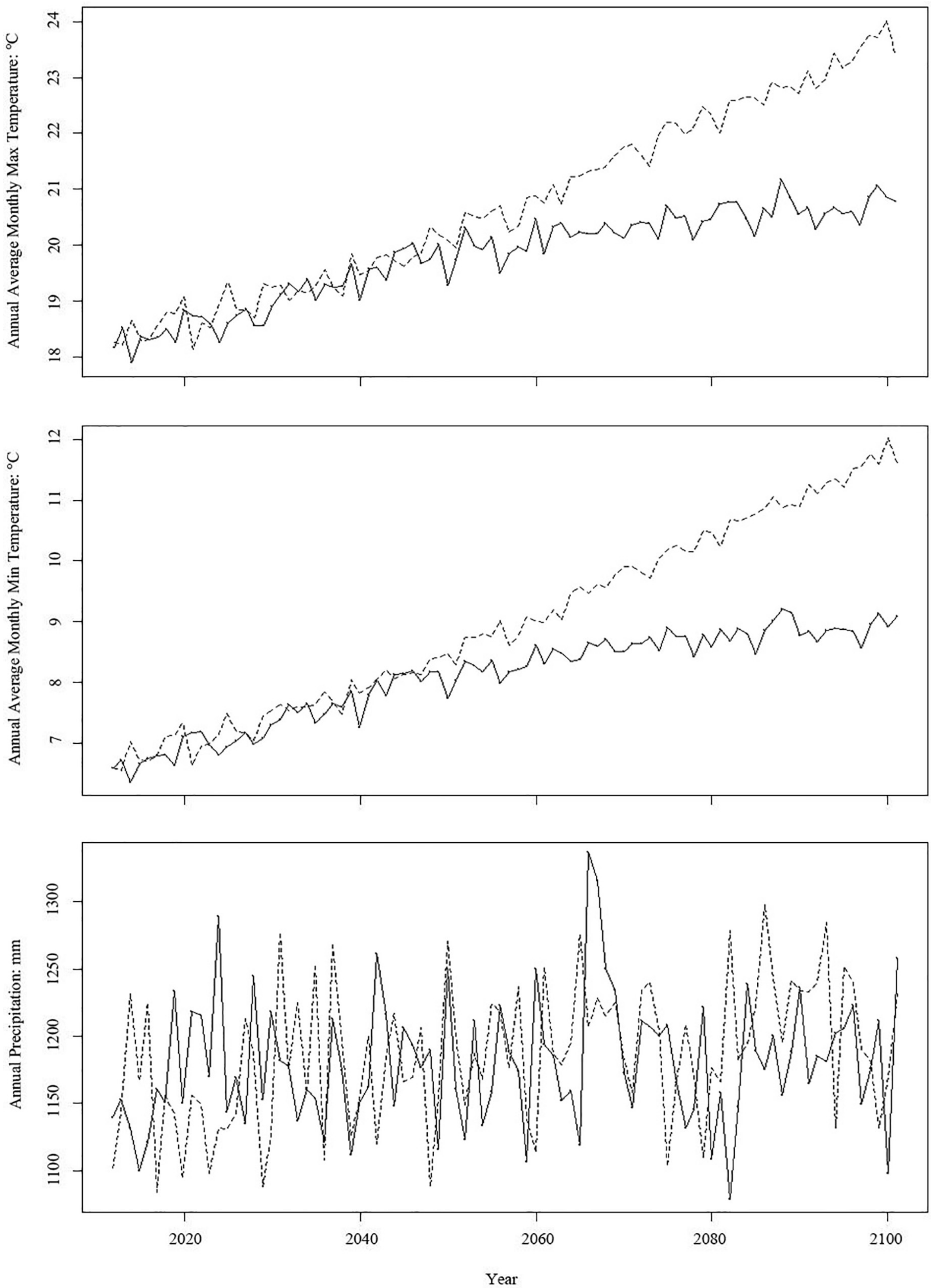

Fig. 1. Climate data simulated by the 20 GCMs in different climate change scenarios from 2012 to 2112, a) average daily maximum air temperature, b) average daily minimum air temperature and c) precipitation. Note: the solid lines are the climate data in RCP4.5, and the broken lines are the climate data in RCP8.5.

Table 1
Description of land use change scenarios simulated in this study.

Scenario #	Original	Land Use History for Spin-up	Converted	Future
S1	Forest (Mixed Forest)	1000-year untouched mixed forest + 1000-year harvested mixed forest	Grassland (Tall Grass)	500-year moderate graze
S2	Forest (Mixed Forest)	1000-year untouched mixed forest + 1000-year harvested mixed forest	Cropland (High Yield Corn)	500-year with moderate fertilizer
S3	Forest (Mixed Forest)	1000-year untouched mixed forest + 1000-year harvested mixed forest	Oil Drilling	20-year oil drilling + 480-year harvested mixed forest
S4	Grassland (Tall Grass)	1000-year low-intensity grazing + 1000-year moderate-intensity grazing	Oil Drilling	20-year oil drilling + 480-year moderate-intensity grazing
S5	Cropland (High Yield Corn)	1000-year low-intensity grazing + 1000-year corn with low fertilizer	Oil Drilling	20-year oil drilling + 480-year corn with moderate fertilizer
S6	Mine Land	1000-year untouched mixed forest + 980-year harvested mixed + 20-year mining	Forest (Mixed Forest)	500-year harvested mixed forest
S7	Mine Land	1000-year untouched mixed forest + 980-year harvested mixed + 20-year mining	Grassland (Tall Grass)	500-year moderate-intensity grazing

CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM5 and NorESM1-M. The medium and high greenhouse gas concentration scenarios were RCP4.5 (emissions peak around 2040) and RCP8.5 (emissions continue to rise throughout the 21st century, Pachauri et al., 2014), respectively. All GCM simulations were downloaded from http://maca.northwestknowledge.net/index.php. The website provides climate data based on the Multivariate Adaptive Constructed Analogs (MACA) which is a statistical downscaling method (Abatzoglou and Brown, 2012). Fig. 1 shows the average climate data simulated by the twenty GCMs in the two climate change scenarios.

2.3.3. Land use change scenarios

In this study, we defined seven land use change scenarios to test the performance of the method described in the previous subsections (Table 1). To estimate the impact of the land intervention on carbon sequestration, we also modeled the carbon sequestration without any intervention as baselines. The baselines for the seven scenarios were defined in Table 2. Different 2000-year land use histories for different scenarios were assumed to initiate the CENTURY model. The mean precipitation and temperature from CRU were used for the first 1888 years. The remaining 112 years were simulated with actual climate data from CRU. After land use conversion occurred in 2012, a total of 500 years were simulated. The climate data were downloaded from IPCC AR5 GCM simulations. The first 88 years were simulated with the actual outputs of GCMs. The mean values of the last 20 years in GCM simulations were used for the rest 412 years. If the land was used for oil drilling, the land was assumed to be occupied for 20 years and gradually restored to original land type after the land occupation. For the abandoned mine land, forest/grass started to grow after 20 years of abandonment in the baseline.

When conducting LCA study, the FU for different land conversion scenarios should be defined based on different proposed products after land use interventions. However, to make a valid comparison among different land use changes, we defined FU as 1 m^2 of land area for all scenarios in this study.

3. Results

3.1. Carbon storage in different scenarios

In comparison to the carbon storage between the two climate change scenarios (RCP4.5 and RCP8.5), carbon storages of land use change scenarios and baselines were generally higher under RCP4.5 scenario than under RCP8.5 (Fig. 2). In S1, S2, S3, S6, SI and SIV, regulate harvest of mixed forest was assumed with a rotation length of 20 years. In comparison to the other land use changes, the harvest activity increased disturbance and variation of carbon storages among the simulations by the twenty GCMs. In S1-S5, the land use conversions induced significant reductions of carbon storage in comparison to their corresponding baselines (Fig. 2a–j). In Fig. 2a, c and d, the lines for baselines and land use change scenarios were well separated. The lines in the other figures (Fig. 2b, e–j) were confounded between baselines and land use change scenarios. However, the averages in land use change scenarios were still significantly lower than in corresponding baselines. In S6, the land use change scenario with aggressive vegetation restoration increased carbon storage quickly, and the averages were higher than in the corresponding baseline (Fig. 2k, l). In S7, the abandoned mine land was restored to grassland instead of mixed forest, the carbon storage remained high in vegetation restoration scenario in the early stage (before 2100), and the carbon storage in the corresponding baseline quickly exceeded the carbon storage in restoration scenario after 2100 (Fig. 2m, n). In all scenarios, a relatively stable status could be approached within the simulated 500-year period (usually after 100 to 200 years of growth).

3.2. Annual carbon sequestration in different scenarios

Fig. 3 shows the differences of the annual carbon sequestration rate between the land use change scenarios and their corresponding baselines. The differences were calculated by subtracting the carbon sequestration rate in the corresponding baselines from the carbon sequestration rate in the land use change scenarios. The simulations of every GCMs were shown in Fig. 3. Although the differences of the

Table 2
Description of baselines in this study.

Scenario #	Original	Land Use History for Spin-up	Future	For Scenarios
SI	Forest (Mixed Forest)	1000-year untouched mixed forest + 1000-year harvested mixed forest	500-year harvested mixed forest	S1, S2, S3
SII	Grassland (Tall Grass)	1000-year low-intensity grazing + 1000-year moderate-intensity grazing	500 moderate-intensity grazing	S4
SIII	Cropland (High Yield Corn)	1000-year low-intensity grazing + 1000-year corn with low fertilizer	500 corn with fertilizer	S5
SIV	Mine Land	1000-year untouched mixed forest + 980-year harvested mixed + 20-year mining	20-year abandon + 480 harvested mixed forest	S6,7

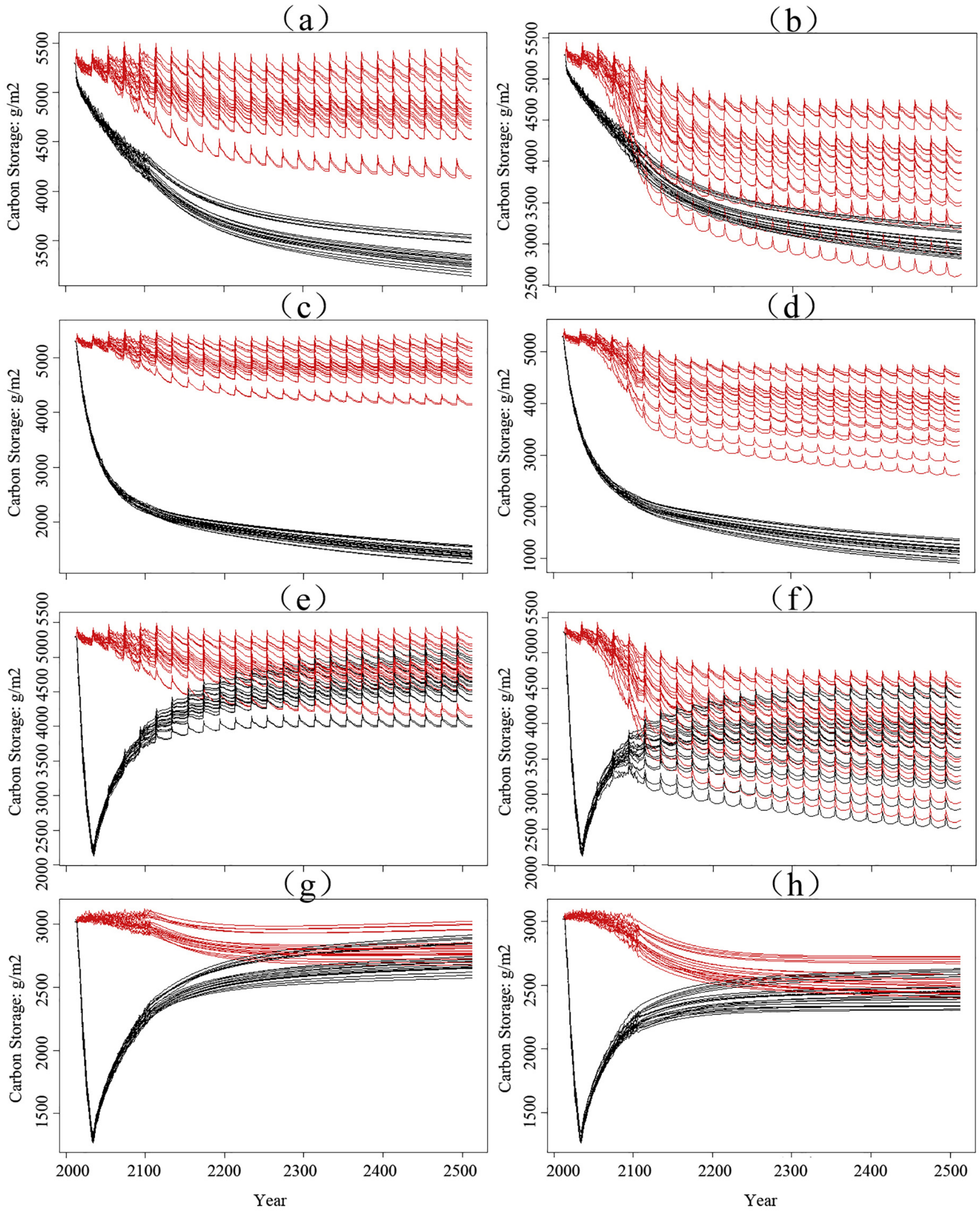

Fig. 2. Carbon storage within the simulation period from the 20 GCMs. Note: The black lines are the carbon storages in the land use change scenarios, and the red lines are the carbon storages in the corresponding baselines.

annual carbon sequestration rates were distinguishable in both climate change scenarios, the patterns were similar between RCP4.5 and RCP8.5. After 100 to 200 years of growth, an equilibrium status was obtained for all scenarios. Before the equilibrium status, the differences increased in S1 and S2. In S3-S5, the values increased at first and decreased later before the equilibrium status. The values in S6 and S7 decreased at first and increased later. In the equilibrium status, the differences of annual carbon sequestration rates were maintained to zero or changed regularly around zero. The difference changed around zero only if harvest activity of mixed forest was included in the scenario.

3.3. CFs in different scenarios

The characteristic factors for all cases can be found in Table 3. Between the two climate change scenarios, the values of CFs had no significant difference in each land use change scenario when the TH was 20-year. When TH was 100- and 500-year, the values were significantly lower in RCP4.5 than in RCP8.5 when the land use change scenarios were S1-S5 and S7. In S6, the values of CFs in TH = 100 and

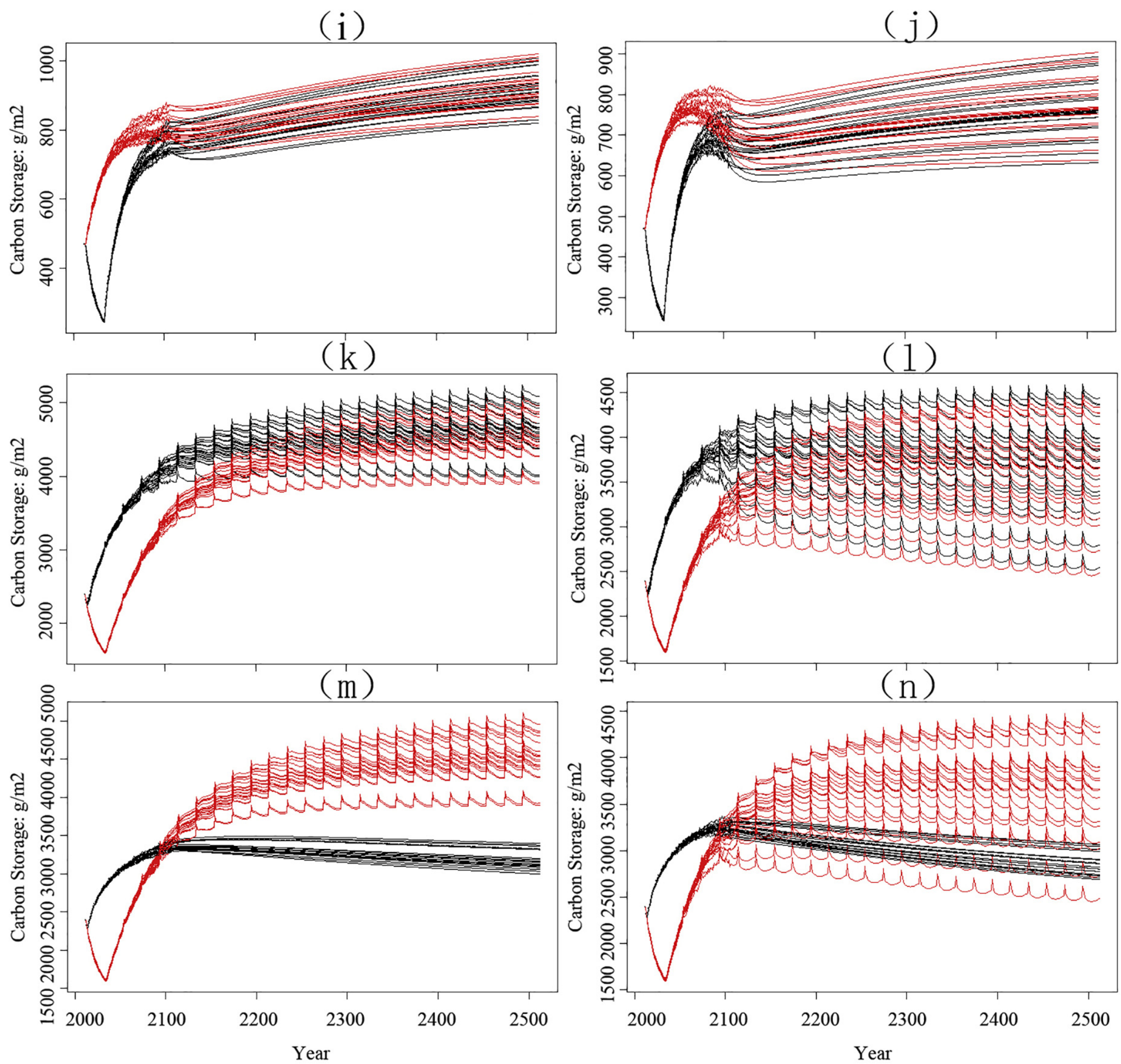

Fig. 2. (*continued*)

500 were higher in RCP4.5 than in RCP8.5. The variances of CFs simulated based on different GCMs were generally higher in RCP8.5 than in RCP4.5 for most of the land use change scenarios. The three exceptions can be found when TH was 100- and 500-year in S5 and TH was 20 in S6. The differences of CFs between the two climate change scenarios were noticeable. However, the changes of CFs among different time horizons were similar in the two climate change scenarios. If forest land was converted to grassland (S1) or cropland (S2), the CFs decreased along with the increase of time horizon. In S6 and S7 where abandoned mine land was changed to forest land and grassland, the CFs also decreased in long time horizon. In S3, S4 and S5, the CFs of oil drilling changed from negative in time horizon 20-year to positive in time horizon 500-year.

3.4. Difference from the previous method

Besides the CFs calculated by the method proposed in this study, Fig. 4 also included the CFs calculated by Arbault et al.'s method (2014). In their method, the interaction effect of ocean–atmosphere systems was excluded from calculating the CFs. In RCP4.5 (Fig. 4a) and RCP8.5 (Fig. 4b), the variations of CFs among different time horizons were similar between methods in Arbault et al.'s study and our study. However, within each land used change scenario, the variation of CFs among different time horizons was more vigorous in our study than in the previous study. In S1 and S2, all the CFs in this study were lower than in the previous study. In S3, S4 and S5, the CFs in this study was lower when time horizon was 20-year and higher when time horizon was 100-year and 500-year. In S6 and S7, the CFs in this study were higher when time horizon was 20-year and lower when time horizon was 100-year and 500-year.

4. Discussion

4.1. Carbon dynamics in different scenarios

In every land use change scenario, higher carbon storage was obtained in RCP4.5 than RCP8.5. In RCP8.5, the higher air temperature was simulated because greenhouse gas emissions continue to rise after 2040. However, no significant increase of annual precipitation was found in RCP8.5. Therefore, the increment of air temperature in RCP8.5 inhibited the carbon accumulation (Zhao and Running, 2010). Among the land use change scenarios, scenarios with forest harvest caused significant and regular changes of carbon storage. The changes can be attributed to carbon storage change which is sensitive to the forest management activities (Fahey et al., 2010). Forest harvest could effectively reduce both aboveground and belowground carbon storage.

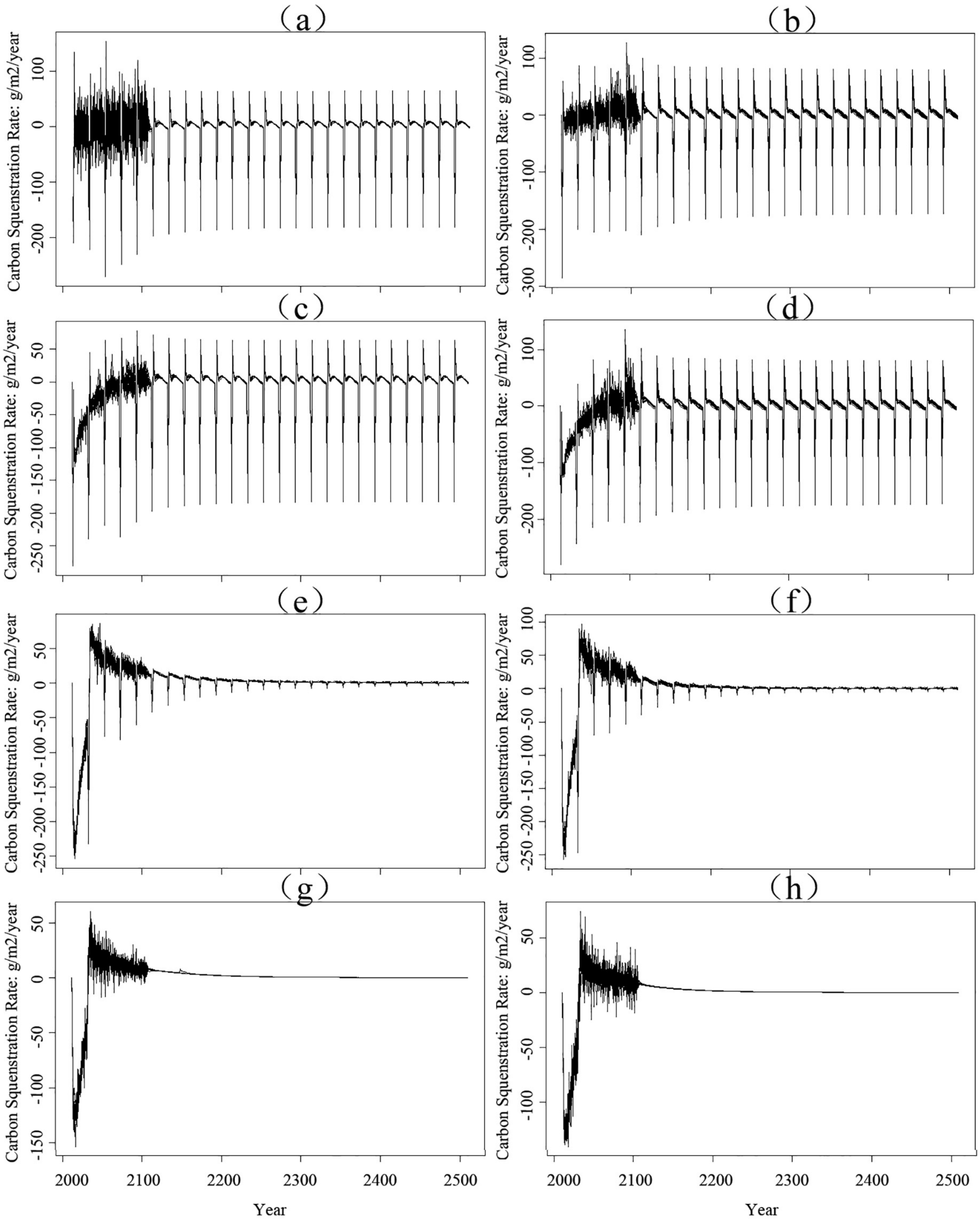

Fig. 3. Different of carbon sequestration rate of different scenarios to their corresponding baselines.

Therefore, carbon storage change under the scenarios with forest harvest activity generally fluctuates with a wider variation.

Land use change could significantly affect the carbon equilibrium of the original ecosystem (Searchinger et al., 2008; Don et al., 2011; Lawler et al., 2014; Woodall et al., 2015). In this study, the differences of carbon storage between land use change and original land use were projected by the CENTURY model. We found that the changes of carbon storage heavily depended on the types of land use changes. Forest to grassland or cropland would lead a net carbon emission. Land occupation for oil drilling would also disturb the original carbon balance and reduce carbon storage. However, when aggressive vegetation restoration was implemented on abandoned mine land, a quick increase of carbon storage could be expected.

Carbon sequestration, as an important ecosystem service, is the main focus of this study. The negative value in Fig. 3 indicated a net carbon loss, and the positive value was a net gain. Similar to the effect on carbon storage, carbon loss was indicated in S1-S5 where the forest was changed to grassland or cropland, and the land was used for oil drilling. After a land use change, a new carbon balance could be eventually established in the new ecosystem (Ciais et al., 2011). The

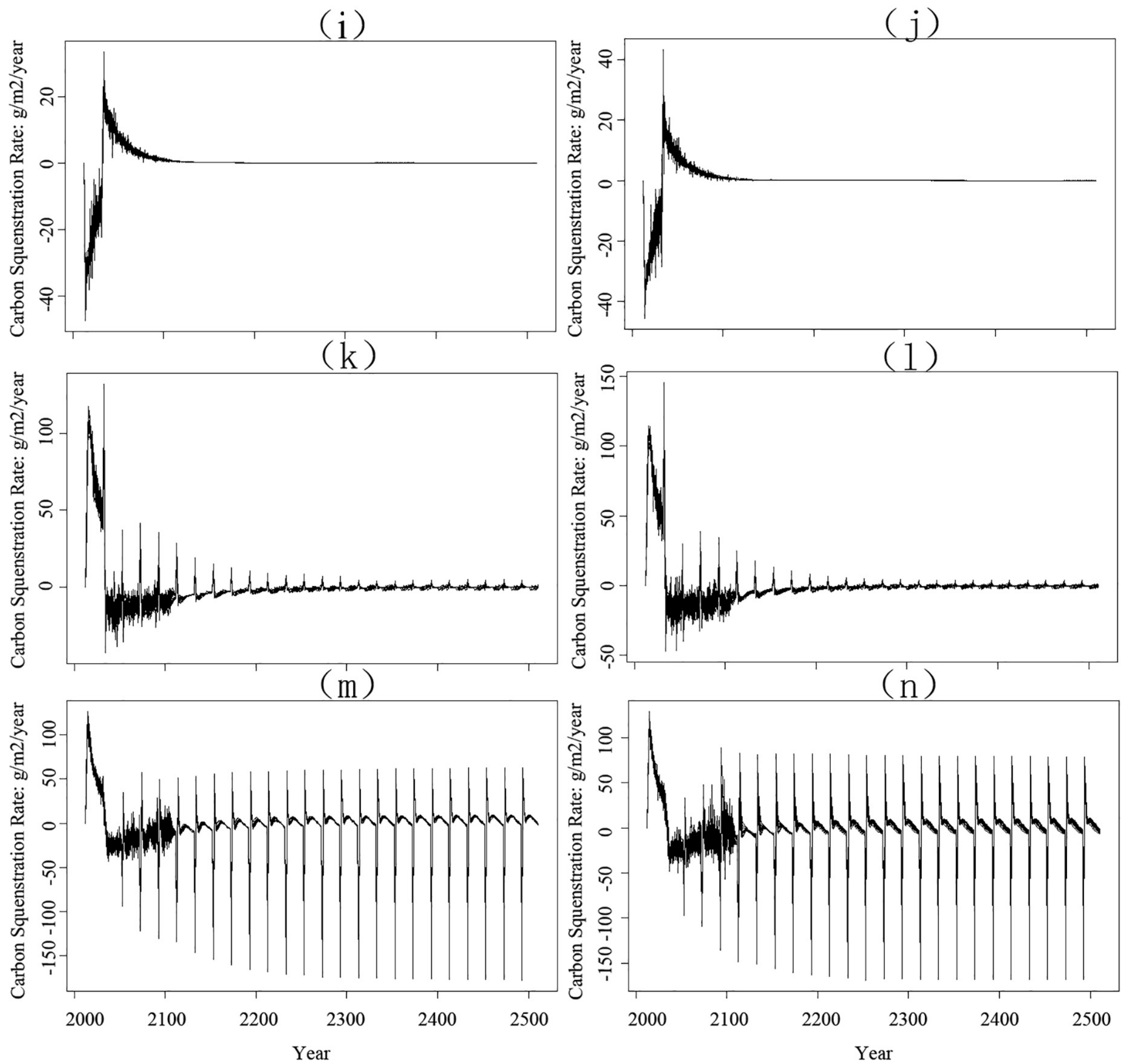

Fig. 3. (*continued*)

equilibrium status was obtained after 100 to 200 years of growth. Therefore, the difference became unnoticeable between land use change scenario and the corresponding baseline. However, the patterns of the differences were changed dramatically in different land use change scenarios. This is mainly because the carbon sequestration highly depends on the type of land use change.

4.2. Characterization factors

The characterization factor is a commonly used coefficient in LCA to account a target impact (Koellner et al., 2013). In this study, the CF was the coefficient for the loss of carbon sequestration. In the comparison of the CFs between the two climate change scenarios, lower CFs were usually found in RCP4.5 in S1-S5. This means higher carbon loss in RCP4.5, indicating that the lower air temperature in RCP4.5 allowed more carbon accumulation in an ecosystem (Zhao and Running, 2010), and undisturbed ecosystem had faster carbon accumulation than ecosystem after land use change.

The negativity or positivity of CFs mostly depends on the type of land use change and time horizon. In short time horizon (TH = 20), the

Table 3
The values of characterization factors (CFs) of land use changes in different scenarios.

	RCP4.5			RCP8.5		
	TH = 20	TH = 100	TH = 500	TH = 20	TH = 100	TH = 500
S1	−438.35 ± 33.02	−1397.97 ± 247.27	−3017.20 ± 458.48	−424.61 ± 34.37	−565.96 ± 537.19	−1524.91 ± 1054.73
S2	−2174.22 ± 27.57	−4509.35 ± 275.34	−6024.91 ± 508.78	−2172.09 ± 27.93	−3537.22 ± 599.76	−4292.49 ± 976.90
S3	−3890.95 ± 29.35	−177.31 ± 165.64	2344.40 ± 30.91	−3886.91 ± 34.24	368.87 ± 271.81	2329.57 ± 35.56
S4	−2308.21 ± 28.79	−201.22 ± 43.72	1286.79 ± 16.92	−2313.21 ± 30.70	−94.91 ± 49.79	1285.63 ± 17.52
S5	−563.09 ± 7.35	163.56 ± 2.51	249.40 ± 3.64	−560.33 ± 8.21	170.13 ± 2.30	252.80 ± 3.45
S6	1816.66 ± 19.47	353.41 ± 56.40	−1090.08 ± 12.65	1816.09 ± 18.62	113.73 ± 134.98	−1102.08 ± 20.36
S7	1586.98 ± 17.88	−1144.96 ± 101.51	−4429.41 ± 471.91	1590.39 ± 19.73	−857.60 ± 260.03	−2940.85 ± 1090.90

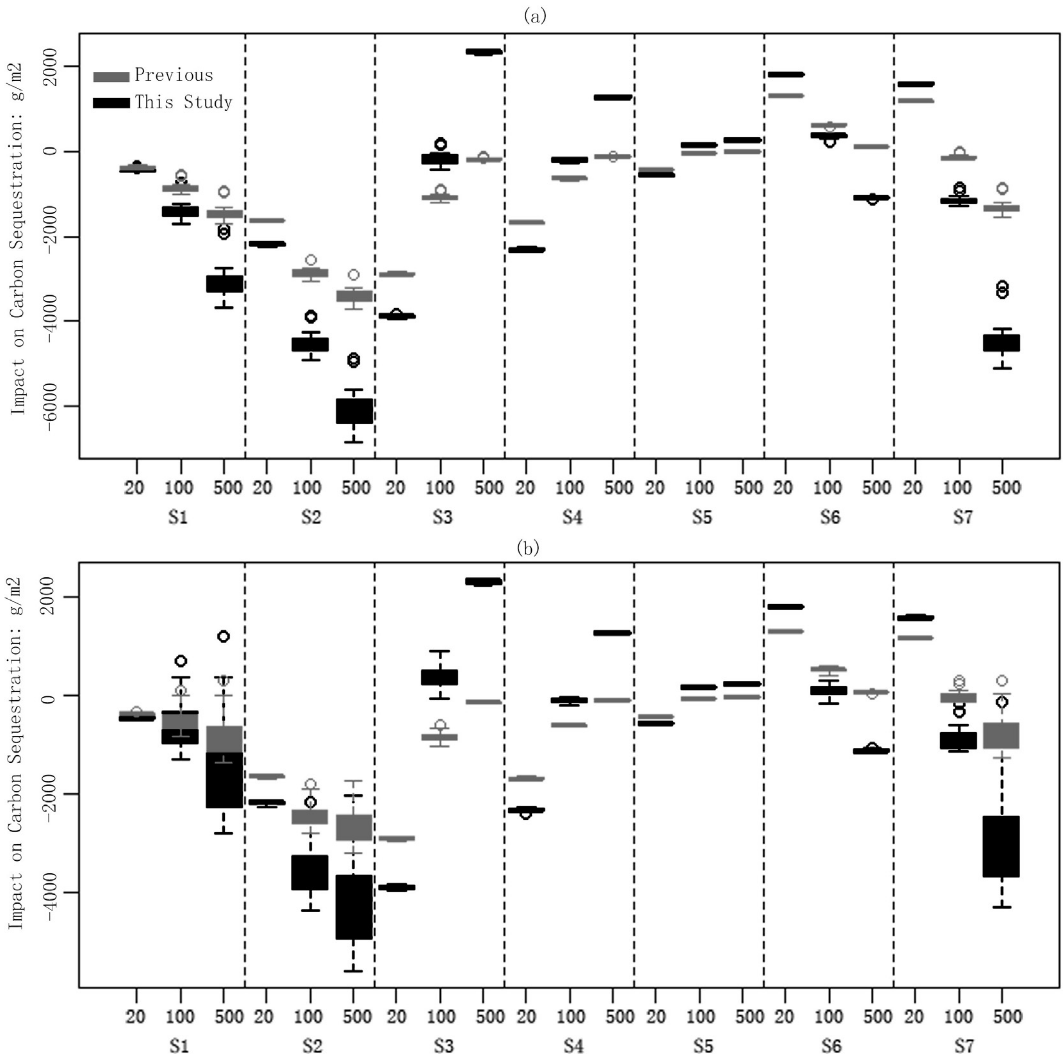

Fig. 4. Difference of characterization factors between previous model and this study. Note: Previous means the CFs calculated by the previous method. This Study means the CFs calculated by the method in our method.

sign of CF was determined by the type of land use change. An aggressive vegetation restoration increased carbon sequestration rate, and positive CFs were obtained. If the land experienced a vegetation degradation (i.e., forest to grassland or cropland, oil drilling), negative CFs could be expected. In long time horizons, the sign of CF was decided by both type of land use change and carbon accumulation of vegetation. If the carbon accumulation in the corresponding baseline was faster than in the land use change scenario, the CF was usually negative when TH = 500.

4.3. Different from the previous method

To illustrate the difference between our method and the method adopted in previous studies, the CFs were also calculated by the previous method (Levasseur et al., 2010; Arbault et al., 2014). In the previous studies, the impact on carbon sequestration was accounted by integrating carbon dynamics model of vegetation. However, their assessments were too conservative in comparison to this study. The reason is that they ignored the carbon dynamics in the atmosphere where the interaction of ocean-atmosphere system could cause significant decay of CO_2 emission (Joos et al., 2013). The pattern of CFs in different time horizons was similar when calculated by methods in the previous study and this study. However, the incorporating of carbon dynamics in ecosystems and in the atmosphere is necessary to increase the weight of impact on carbon sequestration in the future and assess the impact more reasonably.

4.4. The application of this method

In this study, a new approach was proposed to assess the impact of carbon loss due to land use change. All the land used change scenarios were assumed to occur near Nineveh, IN, the USA in 2012. The simulations of carbon dynamics in different ecosystems by the CENTURY model were used as examples to illustrate the application of this method. However, the application of this method is not limited to those types of land use changes in this study. Besides the simulation of the CENTURY model, the other carbon dynamics simulation tools could obtain different carbon dynamics, such as FVS (Dixon, 2002), CBM-CFS3 (Kurz et al., 2009), CO2FIX (Schelhaas et al., 2004) and ForCSv2 extension for the LANDIS-II model (Dymond et al., 2002). Therefore, to determine the most suitable carbon dynamics model for a specific land use change, more validations need to be conducted, albeit the estimation of carbon dynamics is very complex (Adamus et al., 2000). In this study, the vegetations were simulated without any natural disturbance, such as wildfire, pest outbreak. Although the behavior of natural disturbances is difficult to simulate, the consideration of natural disturbances could increase the uncertainty of CFs (Denman et al., 2007).

5. Conclusion

In this study, a new approach was proposed by integrating the carbon dynamics in the ecosystem and the atmosphere. The application and performance of this method were illustrated by seven land use change scenarios. By running the CENTURY model under different climate change scenarios, we found that the carbon storages in RCP4.5 were higher than in RCP8.5. The carbon dynamics obtained an equilibrium status in every scenario after 100 to 200 years of land use conversion. Although the values of differences of the annual carbon sequestration rate were different between the two climate scenarios, the patterns were similar. The types of land use change significantly affected the carbon storage and the difference of the annual carbon sequestration rate. When the characterization factors were calculated for incorporating into LCA, we found the CFs were significantly affected by the type of land use change, climate change scenario and time horizon. In comparison to our method, our study indicated that the estimations by the previous method were more conservative. However, the consideration of carbon dynamics in the atmosphere is necessary for a reasonable assessment of the impact of land use change on carbon sequestration.

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Conflict of interest

The authors declare that they have no conflict of interests.

Authors' contributions

Weiguo Liu and Dexiang Wang conceived the ideas and designed methodology; Weiguo Liu collected the data and analyzed the data; Weiguo Liu and Dexiang Wang led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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